

NASA's In Space Manufacturing Initiative Update and In-Situ Monitoring Development

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**Manufacturing Problem
Prevention Program
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Aerospace Corporation**

Acknowledgements

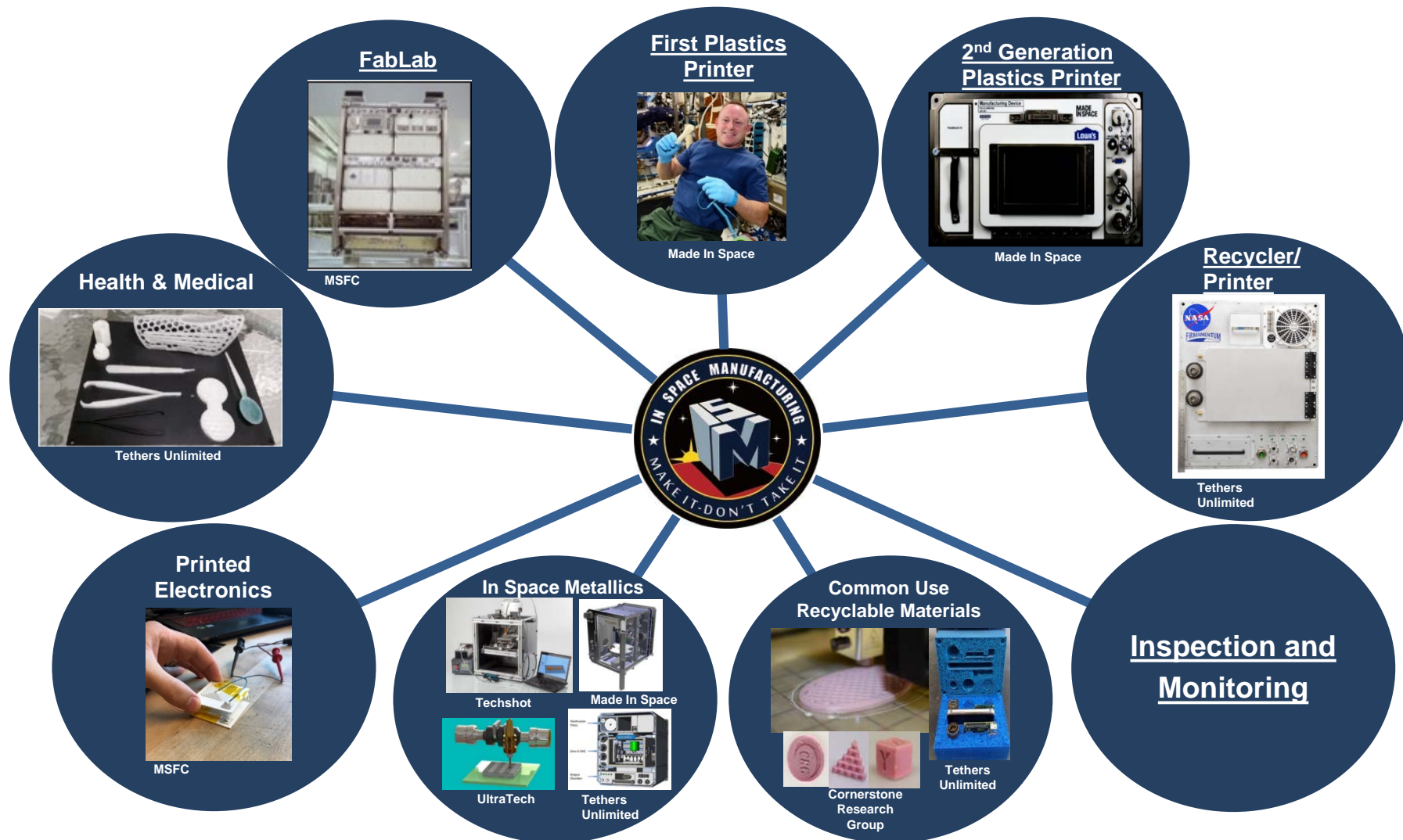
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Agenda

- 1. NASA's In Space Manufacturing Initiative (ISM)**
 - A. ISM Path to Exploration
 - B. In Space Robotic Manufacturing and Assembly (IRMA)
 - C. Additive Construction
- 2. NASA's Plans for Development of Standards for Additive Manufactured Components**
- 3. Summary**

ISM Path to Exploration - Key Thrust Areas





In-space Robotic Manufacturing and Assembly (IRMA) Overview



Concept by Made In Space

Archinaut



Concept by Space Systems/Loral

Dragonfly



Concept by Orbital ATK

CIRAS

A Versatile In-Space Precision Manufacturing and Assembly System

In-Space Robotic Manufacturing, Assembly and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors

A Commercial Infrastructure for Robotic Assembly and Services

Tipping Point Objective

A ground demonstration of additive manufacturing of extended structures and assembly of those structures in a relevant space environment.

A ground demonstration of robotic assembly interfaces and additive manufacture of antenna support structures meeting EHF performance requirements.

A ground demonstration of reversible and repeatable robotic joining methods for mechanical and electrical connections feasible for multiple space assembly geometries.

Team

Made In Space, Northrop Grumman Corp., Oceaneering Space Systems, Ames Research Center

Space Systems/Loral, Langley Research Center, Ames Research Center, Tethers Unlimited, MDA US & Brampton

Orbital ATK, Glenn Research Center, Langley Research Center, Naval Research Laboratory

Status: Teams completed 2-year risk reduction developments. Proposals for flight demo submitted.



Additive Construction Dual Use Technology For Planetary and Terrestrial Applications



US Army Corps
of Engineers.
Engineer Research and
Development Center

Vision: Capability to print custom exploration structures on-demand, on extraterrestrial surfaces, using locally available materials.

Additive Construction with Mobile Emplacement (ACME) NASA



Automated Construction of Expeditionary Structures (ACES) (CERL – ERDC)

ACES-3 demo print ready in Champaign, IL

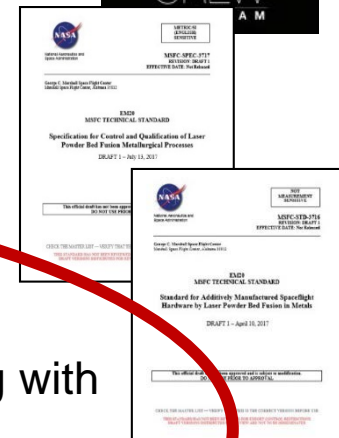


*Paving
the
path
in
exploration*



NASA can not wait for America Makes or other national standards organizations to develop AM standards

- Program partners in manned space flight programs (Commercial Crew, SLS, and Orion) are actively developing AM parts
 - AM parts are currently used for commercial space flight
 - MSFC standard is currently being used for certification via tailoring
- MSFC-STD-3716 lists 65 unique Additive Manufacturing Requirements
- MSFC-SPEC-3717 lists 45 unique Process Control and Qualification Requirements
- Although the MSFC standard was written specifically for the Laser Powder Bed Fusion process it's principles can be applied to any AM process for the purpose of certification
- The NESC formed a team to explore creation of Agency Standards and Specifications for Additive Manufactured (AM) components.
 - This team includes representatives from nine NASA centers along with representatives from the FAA, Air Force, Navy and Army.
 - One standard each for Crewed, Non-Crewed, and Aeronautic Projects
- Separate specification to cover Equipment and Facility Process Control
- Standards are planned to be ready for Agency-wide review in late 2020



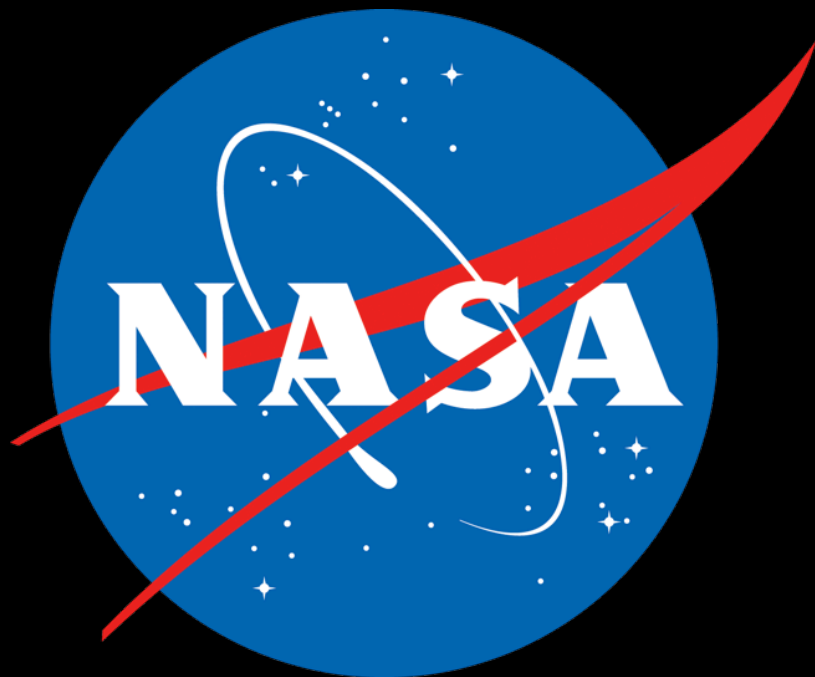
NASA Space Technology Mission Directorate has identified In Space Manufacturing and On-Orbit Assembly as one of eight Key Technology Focus Areas

MSFC is actively working with industry partners to develop ISM capabilities:

- **Within Pressurized Volume:** Reduce the logistics challenges and keep astronauts safe and healthy in transit and on extraterrestrial surfaces (tools; spares; food-safe and medical-grade applications)
- **IRMA:** Add new commercial capabilities in spacecraft construction, assembly, and repair in LEO
- **Additive Construction:** Enable infrastructure to be robotically constructed prior to the arrival of astronauts on the extraterrestrial surface, whether that be the Moon or Mars.

NASA's Development of Standards for Additively Manufactured Components

- MSFC released a Standard and a Specification for AM Spaceflight Hardware which are currently being used for certification via tailoring
- Principles can be applied to any AM process for the purpose of certification
- NESC team to explore creation of Agency Specifications and Standards for AM components
- Standards are planned to be ready for Agency-wide review in late 2020



The First Step: The 3D Printing in Zero G Technology Demonstration Mission



The 3DP in Zero G Tech Demo delivered the first 3D printer to ISS and investigated the effects of consistent microgravity on fused deposition modeling

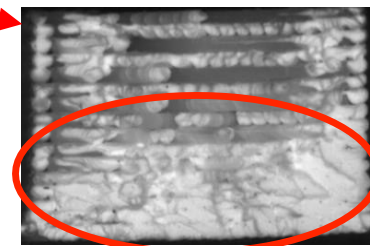
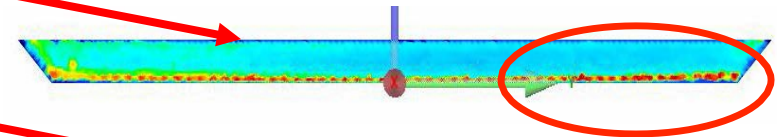
Phase I Prints (Nov-Dec 2014): mechanical property test articles; range coupons; and functional tools



Printer inside Microgravity Science Glovebox (MSG)

Key Observations:

- Tensile and Flexure: Flight specimens stronger and stiffer than ground specimens
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend
- Structured Light Scanning: Protrusions along bottom edges (more pronounced for flight prints)
- Microscopy: Greater Densification of Bottom Layers (flight tensile and flexure)

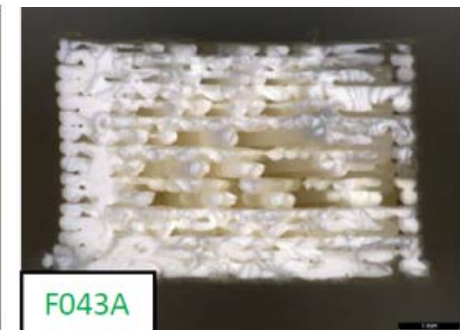
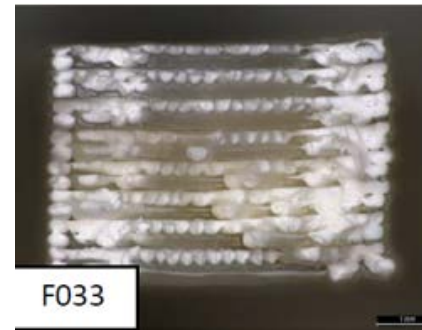


Conclusions

- Z-Calibration distance variation suspected to be primary factor driving differences between flight and ground samples
- Potential influence of feedstock aging are being evaluated further

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)

- Phase II Prints:
 - 25 specimens (tensile + compression) built at an optimal extruder standoff distance.
 - 9 specimens printed with intentionally decreased extruder standoff distance to mimic Phase I flight process conditions
- Key findings:
 - No substantive chemical changes in feedstock
 - No evidence of microgravity effects noted in SEM, SLS, CT analysis. Some internal structure variation between builds and with changes in process settings (primarily compression)
 - All prints to date with 3DP appear to be broadly part of the same family of data
 - Phase I data variations appear traceable to:
 - Differences in manufacturing process settings (extruder standoff distance)
 - Data scatter - characteristic of many additively manufactured materials and processes.
 - Printer variability



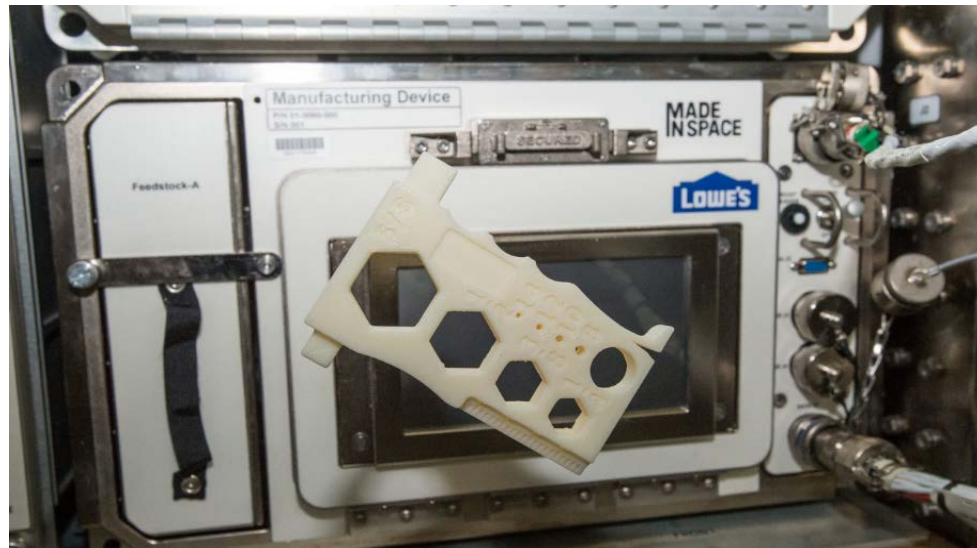
Cross-section of PII tensile specimen manufactured at optimal extruder setting (left) compared with specimen manufactured at a reduced extruder standoff distance (right). Right image has a cross-section characteristic with PI flight prints.

Specimen set	Average ultimate tensile strength (KSI)	Coefficient of variation
Phase II	3.68	6.71
Phase II optimal	3.63	6.61
Phase II off-suboptimal	3.93	0.07
Phase I ground	3.46	1.71
Phase I flight	4.04	5.95

Overall, we cannot attribute any of the observations to microgravity effects.

Additive Manufacturing Facility (AMF)

- Commercial Second Generation Printer by Made In Space for ISS
- Upgrades beyond 3DP include:
 - Capability to print with multiple material feedstocks (ABS, Ultem 9085, and HDPE)
 - Integral cameras and sensors for automated monitoring
 - Maintenance procedures/capability modified to reduce crew time
 - Leveling and calibration done with on-board systems
- Functional parts for ISS experiments and demonstration articles printed on ISS
- Materials characterization task initiated with MIS to develop baseline design mechanical properties on ABS
- Nondestructive characterization of first flight sample set nearing completion at MSFC
- Mechanical property testing of initial set of flight samples will begin soon at Southern Research (see matrix)
- Complete results will be reported at the 70th IAC.



AMF on ISS with printed multi-purpose tool floating in front (photo courtesy of MIS)

AMF Mechanical Property Test Matrix (All tests at RT)				
Type, Orientation	Qty (ground)	Quantity (flight)	ASTM #	Properties
Tension, 0	10	10	D638	Modulus, strength, strain, Poisson's
Tension, 90	10	10	D638	Modulus, strength, strain
Compression, 0	10	10	D695	Modulus, "strength," strain
Compression, 90	10	10	D695	Modulus, "strength," strain
Tension, +/-45 (shear)	10	10	D3518	Modulus, strength, strain, Poisson's
Flatwise tension	10	10	C297	z-direction (through-thickness) tensile strength
Range coupon	2	2	n/a	n/a
EMU fan cap	1	1	n/a	n/a
Total	63	63		



Mission Goal of Refabricator

Demonstrate how the integrated polymer Recycler/3D Printer can increase mission sustainability by providing a repeatable, closed-loop process for recycling plastic materials/parts in the microgravity environment into useable feedstock for fabrication of new and/or different parts.

- Technology Demonstration Mission payload conducted under Phase I, II, II-E, III SBIR contract with Tethers Unlimited, Inc. (TUI)
- Refabricator is an integrated 3D printer (FDM) which recycles ULTEM plastic into filament feedstock through a novel TUI process which requires no grinding.
- Designed to be self-contained and highly automated.
- Hardware turnover for launch to ISS completed 5/31/18.



A complex, integrated manufacturing solution capable of manufacturing precision parts for sparing, repair, and logistics support.

- High degree of autonomy, as crew time is severely constrained for ISS operations.
- Development of inspection and diagnostic capabilities
- *In situ* techniques are under development for ground-based manufacturing systems that can also be leveraged by ISM.

Minimum capabilities as set forth in the broad agency announcement

- On-demand manufacturing of metallics and other materials in the microgravity environment
- Minimum build envelope of 6"x6"x6"
- Earth-based remote commanding
- In-line remote/autonomous inspection and quality control

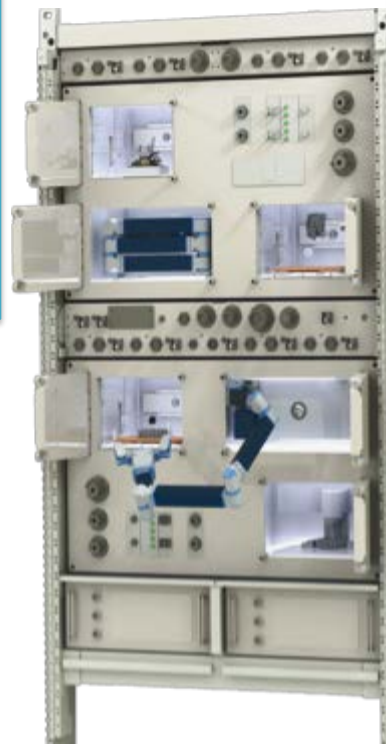
Part of NASA's NEXT-STEP program; intended to follow a phased development approach.

- **Phase A:** Development of a ground-based proof of concept with a design path towards system maturation. (18 month period of performance)
- **Phase B:** Increased emphasis on in-line and possibly *in situ* inspection/monitoring.
- **Phase C:** Mature into a flight demonstration onboard the International Space Station.

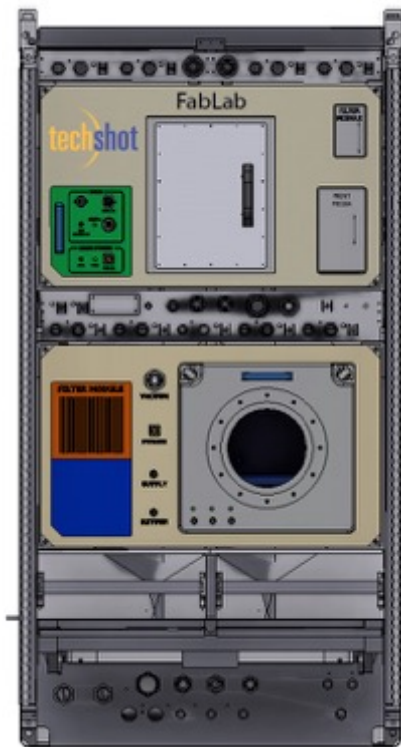
Companies who did not participate in Phase A are eligible to participate in subsequent phases of the Fabrication Laboratory development.

ISM Focal Area: In-Space Manufacturing Manufacturing & Repair

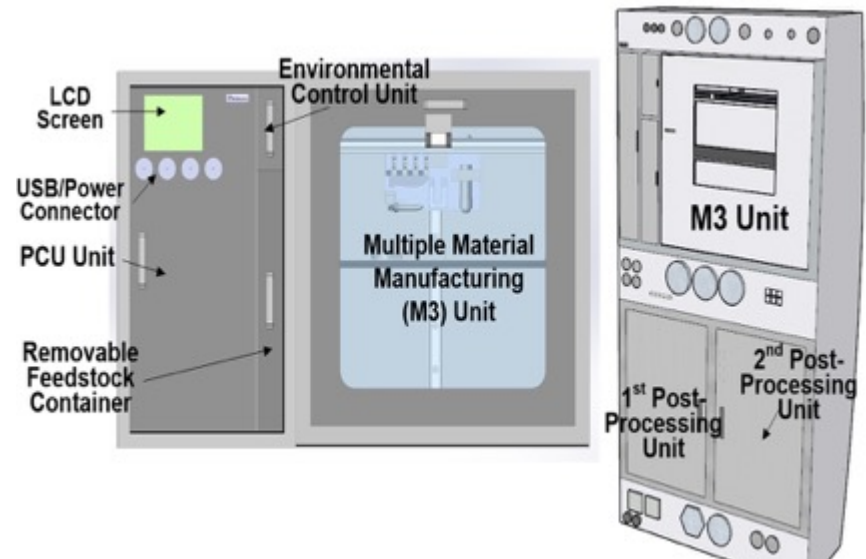
"The Techshot FabLab" - Techshot, Inc. (Greenville, IN)
Partners: Sciperio, GE Global Systems, University of Louisville, Walter Reed Army Medical Center, Uniformed Services University



"Empyrean- Sustainable, In-Space Fabrication Laboratory for Multiple Material Manufacturing, Handling, and Verification/Validation" - Tethers Unlimited, Inc. (Bothell, WA)
Partners: Stratasys, University of Texas El Paso (UTEP), BluHaptics, Vader Systems, IERUS.



"Microgravity Multiple Materials Additive Manufacturing (M3AM) Technology" - Interlog (Anaheim, CA)
Partners: Argonne National Labs, Micro Aerospace Solutions



- Combined funding for the Phase A Awards is approximately \$10.2 million
- These companies will have 18 months to deliver the prototype, after which NASA will select partners to further mature the technologies for an ISS demonstration and 1st generation Exploration system. .

ISM Monitoring and Inspection Capability Development

October 2018

Three FabLab Phase A teams

- Developing technologies for part inspection and process monitoring
- Remote/autonomous commanding
- Feedback and control
- *Note: Capability and approach is being initiated in Phase A, and will be more fully developed in Phase B awards*

Five SBIR Phase I awards

- Maturing low TRL complementary inspection and monitoring technologies
- In-line and/or *in situ* capabilities
- Possible infusion into FabLab Phase B proposals

Ler Technologies, Inc.

Principal Investigator: Dr. Araz Yacoubian

- Feasibility study of an in-situ inspection unit that can be added to an existing additive manufacturing tool, such as an FDM machine, providing real-time information about the part quality, and detecting flaws as they occur.
- The information provided by this unit is used to:
 - Qualify the part as it is being made,
 - Provide feedback to AM tool for correction,
 - Stop the process if the part will not meet the quality, thus saving time, energy and reduce material loss.
- Approach is based on multi-parameter imaging technique to detect flaws in real-time for each AM print layer, such as:
 - Dimensional deviation
 - Micro-structured defects
 - Wide gap between print lines
 - Determine surface finish
- Using multi-parameter approach provides measurement redundancy, maximizing likelihood of detecting defects that may otherwise be missed using a single parameter sensing approach, and avoids false readings.

Cybernet Systems Corporation ***Principal Investigator: Mr. Glenn Beach***

- Approach:
 - Integrated precision scanning of the additive manufactured (AM) parts
 - Feedback of that data into AM layer by layer process control.
- Leverage and productize technology disclosed by the Marshall Space Flight Center a method that determines geometric differences (flaws) between the designed model and the printed part/component by employing IR cameras to collect accurate temperature data that can be validated against valid thermal models.
- Add to that approach by also employing mature but improved NIR optical measurement to implement an additional function on the moving AM extrusion head.
- Employ the 3D data acquired by this embedded scanning sensor to:
 - Provide dimensional verification of part geometry after each deposition pass
 - When employed real time to modify machine control – likely requiring modification of the AM machine's X, Y, Z, and feed rate controlling mechanisms that have to be different depending on ambient conditions (temp, humidity, and gravity) and deposited materials (plastic and plastic emulsion material differences).
- Goal: Augment Space Manufacturing AM process controls with verifiable feedback enabling improved process stability and part quality to significantly reduce the risk associated with complex AM parts, especially critical hidden internal geometries or other features not readily measured with non-destructive tests/measurements.

MetroLaser, Inc.

Principal Investigator: James Trolinger

- **Approach:** Develop a non-destructive evaluation method based upon acoustical signatures that can perform in space, in-situ, and post production and is equally applicable to both metallic and non-metallic AM.
- Combine Laser Doppler vibrometry with vibrational resonance spectroscopy to extract acoustical information from exposed layers during the printing process to characterize the part.
- Demonstrate feasibility by experiment and computer simulation.
 - Component samples ranging from acceptable to unacceptable will be produced and fully analyzed with complex inspection and diagnostic tools to verify the mechanical and structural properties
 - Associated acoustical signatures will be correlated with various stages of contamination and defects.
- Determine how well the acoustical signature of a reference part can be used to certify additional parts arising from subsequent production.
- Show how such a system can be interfaced with a printing machine and operated in a space environment.

Made in Space, Inc.

Principal Investigator: Michael Snyder

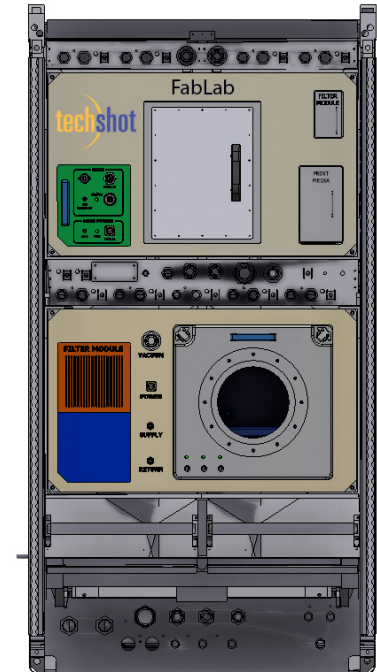
- MIS developed, owns and operates a commercial Additive Manufacturing Facility (AMF) aboard the ISS
- MIS developed quality processes over multiple years of operation that are key to the successful operation of AMF and ensure the success of printing in the microgravity environment including:
 - Ground testing
 - Computer modeling
 - Simulations of the final product to optimize manufacturing on orbit.
- MIS has extensively researched new Verification and Validation (V&V) methods to confirm fabricated components meet the rigorous standards required for aerospace applications.
- Building on the successes of AMF and **SAMEE**, a DARPA funded SBIR Phase I TDP, **AMARU** would enhance the state of the art V&V methods by combining and integrating advanced sensor technology and Siemen's industry leading NX software tools.

Cornerstone Research Group, Inc.

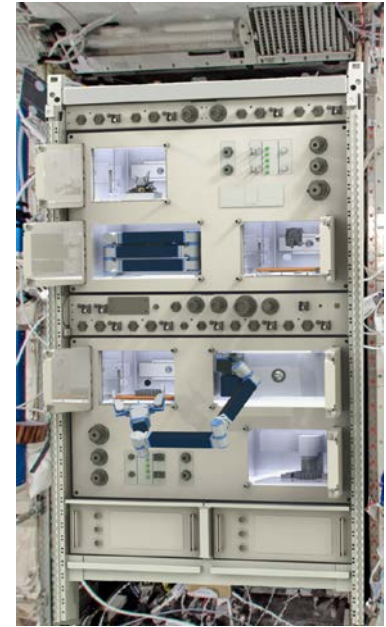
Principal Investigator: Dr. Ryan Snyder

- **Approach:**
 - Applies sensors, hardware, and software algorithms to monitor and adjust feedstock production AND printing processes in real time
 - Certify feedstock
 - Certify print quality.
- Hardware and software developed on this program by CRG will be integrated into systems already being developed to support NASA's ISM on complimentary efforts.
- CRG's proposed approach will initially be applied to FDM feedstock production and print quality, but is applicable to other AM processes using the same control hardware and software with different sensor inputs.

Techshot is a technology development company that primarily serves customers working in microgravity. The company's FabLab effort is focused on producing a ground-based prototype with the ability to mature into a flight demonstration aboard the International Space Station (ISS) within three years. The Techshot FabLab will be compatible with the space station's EXPRESS Racks. Remotely-controlled operations from Earth will manufacture multi-material components, including metals, ceramics, plastics and electronics.



The Tethers Unlimited, Inc. (TUI) Empyrean FabLab increases astronaut efficiency by providing autonomous processing and verification and validation services in a system designed for microgravity operation aboard the ISS. The TUI-led team will develop the Empyrean FabLab to support NASA's long-duration and deep-space manned missions with capabilities for multi-material manufacturing and recycling. The Empyrean team will focus on a suite of support technologies for microgravity-enabled multi-material manufacturing, including robotic handling, quality control, autonomy, and teleoperation capabilities. These capabilities will enable sustainable in-space manufacturing in support of long-duration crewed missions, while minimizing demands upon astronaut time.



Interlog Corporation (Interlog) will develop the Microgravity Multiple Materials Additive Manufacturing (M3AM) technology to provide on-demand manufacturing solutions for fabrication, maintenance, and repair on space missions. M3AM is capable of manufacturing various aerospace-grade metallic parts such as Aluminum, Titanium, Nickel, and other metallics. M3AM can also bond dissimilar materials (e.g., metals, glass epoxy, flexible ceramics). M3AM is enabled by Interlog's proprietary manufacturing technique that additively constructs a part via a focused bonding-energy mechanism. M3AM seeks to offer multi-material AM on a single platform, autonomous operation, dissimilar material bonding for electronics and PCB (Printed Circuit Board) fabrication as additional features, autonomous part removal, and multiple material feeding mechanisms.

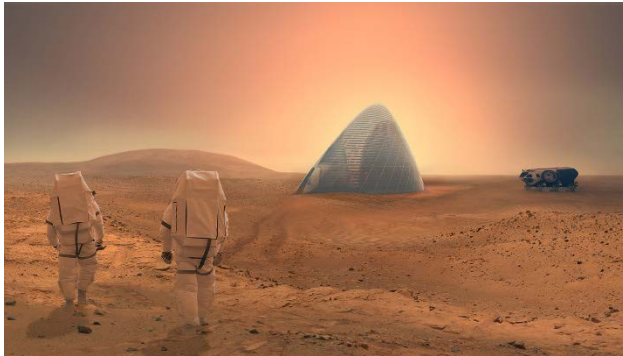
NASA'S 3D-PRINTED HABITAT CHALLENGE

A NASA CENTENNIAL CHALLENGE

NASA's 3D-Printed Habitat Challenge is a competition to design and print habitats that could house humans as they live and work in space and here on Earth.

www.nasa.gov/3DPHab

Phase 1: Design Competition
Completed Sept. 2015
\$40,000 awarded



1st Place: SEArch and Clouds AO

Phase 2: Structural
Member Competition
Completed 9/2017
\$701,024 awarded



1st Place

Foster + Partners | Branch Technology

Phase 3: Structural
Member Competition
Ongoing; 5 sub-levels
\$100,000 awarded to date



**Level 1 BIM 1st Place:
Zopherus**



**2nd Place:
Gamma**



**3rd Place:
LavaHive**



2nd Place

Pennsylvania State University



**2nd Place:
AI.
SpaceFactory**

